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PROGRESS TOWARD PRACTICAL AC AND DC JOSEPHSON VOLTAGE STANDARDS AT NIST

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Abstract: For the past 10 years NIST has been developing the next generation of voltage standard systems based on arrays of normal-metal barrier Josephson junctions. We have developed stable, programmable dc standards capable of providing intrinsically stable voltages up to 3.5 V. The first ac Josephson standards have also been demonstrated at audio frequencies with output voltages of 136 mV rms and part per million (ppm) accuracy. We describe the features and characteristics of these systems as well as the Josephson junction and system technology that makes them possible.

Key words: superconductor, Josephson array, voltage standard, microwave, waveform synthesis.

1. INTRODUCTION

The first step that enabled these new Josephson systems was the demonstration that superconducting-normal metal-superconducting (SNS) junctions could be made with sufficient uniformity to yield superconducting Josephson array circuits with tens of thousands of junctions [1, 2]. The success of these SNS junctions led to the first stable dc programmable Josephson voltage standard, of which, there are now four systems currently in operation at three different national metrology laboratories [3]. We also have been developing a Josephson digital-to-analog converter that can be used for ac voltage metrology and for precision voltage waveform synthesis, which we call the Josephson Arbitrary Waveform Synthesizer [4-6].

Both the dc programmable system and the waveform synthesizer are being developed for metrology applications, namely to calibrate and characterize high-performance dc, audio, and rf electronic instruments, like thermal transfer standards, spectrum analyzers, digital-to-analog and analog-to-digital converters, amplifiers, and power meters. Although these new Josephson systems can produce dc and ac voltages with unprecedented accuracy, the primary challenge has been to achieve higher practical voltages to adequately address the needs of the desired applications. We are accomplishing this by vertically stacking the junctions and thereby increasing the junction density. In this paper, we will describe the progress made toward improving the two new Josephson systems.

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2. PROGRAMMABLE DC JOSEPHSON VOLTAGE

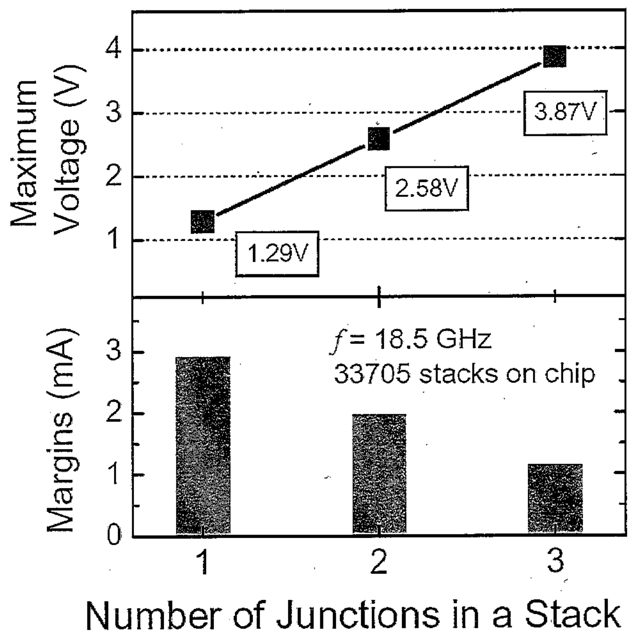

Fig. 1. Maximum programmable voltages and operating current margins measured at 18.5 GHz in single-, double-, and triple-stacked junction circuits. Each 1cm × 1cm chip contains 33 705 stacks divided into 13 array cells, with a trinary-logic design for high voltage resolution. The margins apply to full chip operation, namely the current range over which all junctions on the chip are simultaneously biased on a non-zero quantized voltage step [8].

STANDARD SYSTEM

NIST has made a number of improvements to quantum-based programmable dc voltage standards over the past few years. Most importantly, we have increased the output voltage of these Josephson voltage standards by developing nano-stacked Josephson junction arrays. By vertically stacking these normal-metal barrier junctions we increase the junction density, which in turn increases the output voltage per array and also the output bandwidth for ac operation. Recently, we have demonstrated triple-stacked junction circuits with 101,115 junctions [7-8]. This has allowed us to more than triple our dc output voltage from 1.1 V to 3.5 V with stable output voltage over a 1 mA current range. We have made significant progress in understanding the physics of high-density arrays [9-10] and have demonstrated uniform arrays of 10-junction stacks [11]. By improving yield and uniformity of even taller stacks we hope to achieve 5 V output in 2005 and 10 V in 2006.

We have also improved the performance of our programmable standards by using a new circuit design and new packaging technology. The new "high-resolution" circuit is based on a trinary logic design which takes advantage of the three voltage states of the junction and results in a 50-fold improvement in voltage resolution from 4 mV to 77 μV [8]. We have also developed a new flexible, microwave-compatible, "flip-chip on flex" cryopackage which dramatically improves electrical contact reliability by replacing less-reliable press contacts with direct soldered connections to the chip, thereby improving the service life of the programmable systems. This technique eliminates the most common failure mode for our Josephson circuits: degradation and variation of the contact resistances of the chip pads over time due to mechanical wear.

3. AC JOSEPHSON VOLTAGE STANDARD SYSTEM

NIST is implementing the Josephson arbitrary waveform synthesizer as an ac Josephson Voltage Standard (ACJVS). The system can generate a variety of precision bipolar voltage waveforms, including dc voltages as well as ac sinewaves, so that the system can be used as a quantum-based voltage source for ac metrology. Over the past few years we have demonstrated precision measurements of synthesized sine waves. Using two-series connected arrays with 8200 total junctions, we have demonstrated 242 mV peak (171 mV rms) output voltage at about 3 kHz and measured -93 dBc [dB below the fundamental (carrier)] harmonic distortion with a Fast Fourier Transform spectrum analyzer. Using single-junction un-stacked arrays and an ac-dc transfer standard, we have demonstrated 136 mV rms ac voltages at the level of a part in 10^6 for eight required bias parameters [12].

We are now working toward demonstrating low uncertainty, reproducible 100 mV rms voltages at frequencies from 1 kHz to 50 kHz in order to improve NIST's low-voltage ac calibration service. We are also using stacked-junction arrays to improve the performance of ac pulse-driven circuits [13]. These resulting shorter-length arrays increase the useful output frequency by reducing the undesirable voltage signal caused by transmission line inductance.

3. CONCLUSION

These two new Josephson voltage standard systems will improve ac and dc voltage metrology with their novel features and reduced uncertainty.

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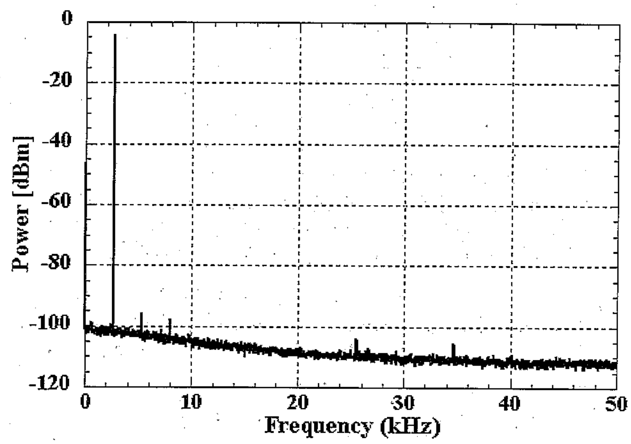

Fig. 2. Spectrum of a 200 mV peak 2.6 kHz sine wave produced from two coupled 4208 junction double-stacked arrays (for a total of 8416 junctions). The distortion harmonics are -92 dBc, indicating that the circuit still has a small operating margin [13].

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